MATERIALS PROCESSING UNDER ZERO GRAVITY, AN ASSESSMENT AFTER SKYLAB

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Skylab will live in the history of space flight as the turning point between two eras. The first era had belonged to the development of space flight techniques, and to the exploration of some of our neighbors in space. The next era will belong to the utilization of our space flight capabilities for science, for communications, for Earth observations, and for materials processing under weightlessness.

Yesterday's sessions dealt with the program in zero-gravity materials processing which was performed on Skylab, and with the very encouraging results of this first round of experiments. In today's presentations, the lessons learned from this first materials program will be discussed, as well as plans for further experiments under zero-gravity on rockets and satellites of the future.

For several hundred years, man has already carried on a modest, but successful program of zero-gravity materials processing. By allowing a finely dispersed spray of molten lead to solidify while the droplets are falling freely, tiny spheres can be produced as they are needed by bird and rabbit hunters for gunshot. Surface tension, without competitive gravitational forces, makes the droplets assume spherical shapes while they are exposed for about a second of time to a state of zero-gravity.

There is no apparent need at the present time for better gunshot. However, there are other good reasons why the processing of materials under zero-gravity conditions is moving rapidly into the frontline of interest and effort of materials experts. First, in many instances our modern materials technology has reached limits of improvement which are clearly set by the effects of gravitational forces. Second, the achievements of the space flight program are now providing opportunities of performing experiments under nearly complete weightlessness for extended periods of time. Third, materials processing experiments on Skylab have yielded results in several fields of zero-gravity materials processing which are extremely encouraging.

A need for better materials seems to arise whenever high strength, or high thermal resistivity, or high precision, or high sensitivity, or high efficiency of a system is required. Some examples are listed in Table 1. Of particular interest are semiconductor materials which should be purer, larger, and of greater homogeneity than those which we have today. Better semiconductors would mean substantial progress in large computers, television systems, power generation and conversion, communication equipment, electric automobiles, and many other technical systems. Metals, alloys, and plastics of higher strength are needed for high temperature turbine blades, for structural and functional elements of nuclear reactors, for artificial human organs, for oil drilling equipment, for precision tool machines. High purity glasses with large coefficients of refraction, and other optical materials with special features, are required for power lasers. If a powerful laser bean is generated in a crystal or transmitted through an optical element, even a minute bit of impurity leads to local absorption of radiative energy which may cause the explosive destruction of the system. Alloys and compounds of certain metals which do not form under normal conditions are of great interest because some of these new substances may include superconductors which become superconducting at temperatures above that of liquid hydrogen. Such superconductors would be of extreme importance for the transmission of electric power at minimal losses.

It would be wrong, however, to look at materials processing experiments only from the viewpoint of immediate applications. Materials science is a genuine science with all the challenge of potential new insights into the secrets of nature, a quality which has always distinguished true science. In following the lure of research and discovery, the scientist does not know at the outset where his work will take him, and what its results will be. He knows, however, that this work will make him wiser, and that it will help eventually to make life better and easier for many others. In this effort to gain more fundamental knowledge of the world that surrounds him, man follows a law to which he has been subject since his early beginnings. The materials scientist, in studying the behavior of materials under the pure and almost abstract conditions of weightlessness, follows that very same law.

Forces of gravity influence a variety of processes which occur in liquids and gases. The internal structures of solids are not much affected by the presence or absence of gravitational forces; however, substantial effects of weightlessness are realized when diffusion, convection, sedimentation and heat conduction occur, when liquids solidify, or when crystals form from a liquid or gaseous phase. Some of these processes are listed in Table 2.

A number of materials processing studies under zero-gravity were made during past years by pioneers of materials sciences in laboratory free fall experiments, in drop towers, during short parabolic airplane flights, and on sounding rockets. The real opportunity for zero-gravity experimentation arrived with Project Skylab. A Materials Science and Manufacturing Program was established as part of this project; Principal Investigators were selected, and no less than 14 different experiments were performed on the three Skylab missions in a facility shown in Fig. 1.

Details of these experiments and of their results were the subject of yesterday's presentations. For those who took part in the Skylab Materials Program, the results are highly gratifying. However, we feel that the positive results of the materials program on Skylab should not be a reason for celebration and complacency. Primarily, this success represents an obligation, even a kind of mandate, to continue the good work. The Skylab experiments were exploratory at best. Dimensions, thermal conditions, concentrations, time histories, and other parameters were not at all optimized, simply because of lack of sufficient knowledge. The fact that the experiments did yield such impressive results indicates that the experimenters used good judgment and had a fair share of luck, but it also proves that zero-gravity materials processing is indeed an extremely promising and fruitful field for further endeavor. We have just cracked the door into a new world of science and technology full of potential success, and we feel that we must continue to make our way into this new world.

Skylab experiments proved very drastically that presence or absence of gravitational forces makes a substantial and even decisive difference in a number of material processes. Fig. 2 shows cross-sections through weld grooves in a piece of stainless steel. In the zero-gravity sample, the transition zone between the weld and the bulk material looks quite different, and in fact much better, than in the ground-produced sample. An example of a space-grown single crystal of indium-antimonide is shown in Fig. 3. Careful study of this crystal has indicated that a far higher degree of purity, homogeneity, and freedom from lattice defects has been achieved in this crystal than in any Earth-grown crystals of similar composition. Another example of a single crystal, grown out of the vapor phase under zero-gravity conditions, is illustrated in Fig. 4. This germanium-selenium crystal has a length of about 20 millimeters. It is completely smooth and homogeneous throughout. If grown on Earth under similar conditions, germanium-selenium crystals remain small, and they assume shapes which indicate a high degree of stress and inhomogeneity, as illustrated in Fig. 5. A particularly impressive example of the disturbing influence of gravity is shown in Fig. 6. The upper part of this sample is a tellurium-doped crystal of indium-antimonide, manufactured under Earth conditions. The striations indicate the layered deposition of the tellurium dopant, caused by an interplay of diffusion, convection and sedimentation between the dopant and the bulk material during solidification. Needless to say that this local variation of the dopant concentration is extremely undesirable when a part of this crystal is to be prepared for use as a semiconductor element in an electronic apparatus. The lower part of this sample was melted under zero-gravity conditions.

After remaining some time in the molten stage, it was allowed to resolidify, still under zero-gravity. During that process, the striations disappeared completely, at least within the resolution of this microphotograph. Elimination of gravitational forces removed the disturbance of diffusion by convection and sedimentation, with the result that the dopant distributed in a completely homogeneous fashion throughout the sample. For materials scientists and for solid state physicists, this picture is equivalent to a bold dream that has come true. A similar feeling may be aroused in the minds of superconductivity experts when they see the picture in Fig. 7. Two metals of very different densities, gold and germanium, were mixed and melted together under zero-gravity conditions. In a ground-based laboratory, the two metals would immediately separate because of the difference in their densities, gold accumulating at the bottom and germanium floating on top. For this reason, an alloy cannot be obtained on Earth if the two are melted together in a container. In the Skylab experiment, the two did alloy; in fact, they formed a fine dispersion, as shown in the microphotograph of Fig. 8. Several places were found in this specimen where a gold-germanium compound had formed, a substance that had not been known from bulk samples heretofore. This compound even shows superconductivity! Admittedly, it becomes superconducting at a very low temperature, 1.7° K, but from all previous experiences a higher transition temperature cannot be expected of a binary compound of this kind. Still, the result of this gold-germanium experiment proves that superconductors can be produced in space that cannot be manufactured on Earth.

Encouraged by these very positive results on Skylab, the program planners for materials science made plans to accommodate a set of zero-gravity materials processing experiments on the next manned space system, the Apollo-Soyuz Test Project. These experiments, listed in Table 3, are still of an exploratory nature, although they are utilizing the experience and the results gained from the Skylab experiments. A big leap for zero-gravity materials science and technology will come with the Shuttle-borne Spacelab in the early eighties. A broad program of materials processing work is being prepared for Spacelab, as shown in the Table.

This program, in contrast to the programs on Skylab and the Apollo-Soyuz Test Project, will not be limited to a few flights; it will continuously evolve through the years, and it will include exploratory experiments, purely scientific investigations, pilot projects for manufacturing of useful quantities of materials, and eventually even production runs for larger quantities. Instruments and facilities can be accommodated within the Spacelab capsule where scientists and engineers can personally tend to the experiments, and also on the open Pallet where automated systems will be mounted. Fig. 9 shows the Shuttle with its large payload bay. A sketch of the Spacelab and the adjacent pallet is shown in Fig. 10. Some tentative figures for the quantities of materials that can be processed on the Shuttle are listed in Table 4. These figures show that the capabilities of the Shuttle for zero-gravity production runs are not all unrealistic for such very special materials as semiconductors, high temperature alloys, glasses for lasers and infrared optics, superconductors, and biomedical vaccines. Yearly quantities required of these materials range from a few hundred to several thousand kilograms per year. At least for a number of years, the Shuttle will be adequate to provide the zero-gravity facility for such a program.

In conclusion, it may be appropriate to quote a statement by Professor Goldberg, astronomer and Director of the Kitt Peak Observatory, who participated in the solar physics program of Skylab. When the Skylab Project had come to its end, he said: "When it all began, many of us were doubtful whether this combination of men and instruments in an orbiting station would lead to a success. Now, we are convinced, and we are deeply impressed. In fact, Skylab has made sincere believers out of us."

It seems that a very similar statement can be made for those who have participated in the materials processing program carried out under weightlessness on the orbiting Skylab, and who are looking forward now to an expanding program on future spacecraft.

TABLE 1 SPECIFIC MATERIALS TO BE PRODUCED UNDER WEIGHTLESSNESS

MATERIALS	USES
ALLOYS OF HIGH YIELD STRENGTH AND HEAT RESISTANCE	TURBINE BLADES, REACTOR COMPONENTS, STRUCTURAL ELEMENTS
GLASSES OF HIGH REFRACTIVE INDICES AND HIGH PURITY	OPTICAL INSTRUMENTS, LASERS, FIBER OPTICS
SEMICONDUCTORS OF GREAT HOMOGENEITY AND LARGE SIZE	ELECTRONIC SYSTEMS, COMPUTERS, LASERS, POWER CONVERSION
SUPER CONDUCTORS WITH TRANSITION TEMPERATURES ABOVE $20^{o}K$	ELECTRIC POWER GENERATION AND TRANSMISSION
BIOMEDICAL SUBSTANCES OF HIGH PURITY	VACCINES, SERA, BIOLOGICAL AND MEDICAL RESEARCH

TABLE 2 GRAVITATIONAL FORCES INFLUENCING MATERIALS PROCESSING

- CONVECTION
- DIFFUSION
- TURBULENCE
- BUOYANCY
- HEAT CONDUCTION

- LAYERING
- SEGREGATION
- LATTICE DEFECTS
- BUBBLE EFFECTS
- CRYSTAL GROWTH

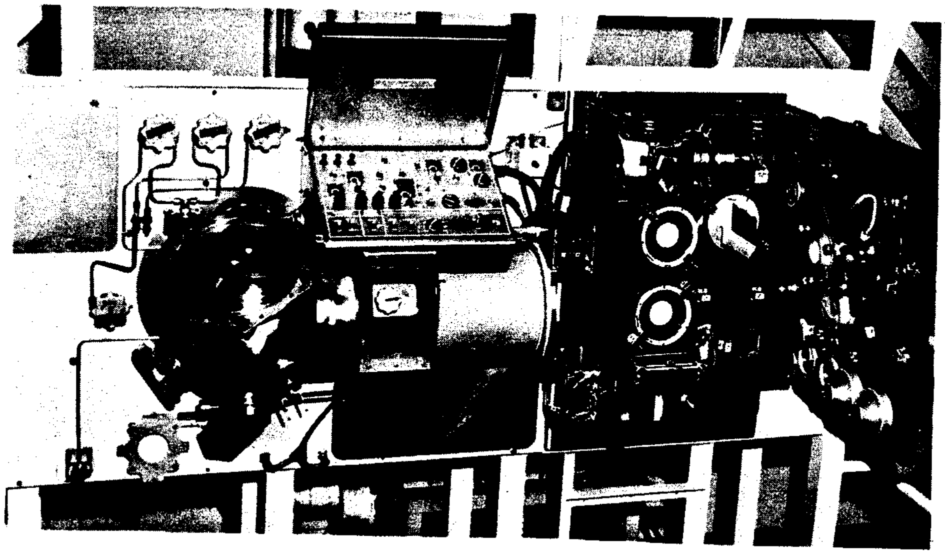


FIGURE 1 M512 SPACE PROCESSING FACILITY ON SKYLAB

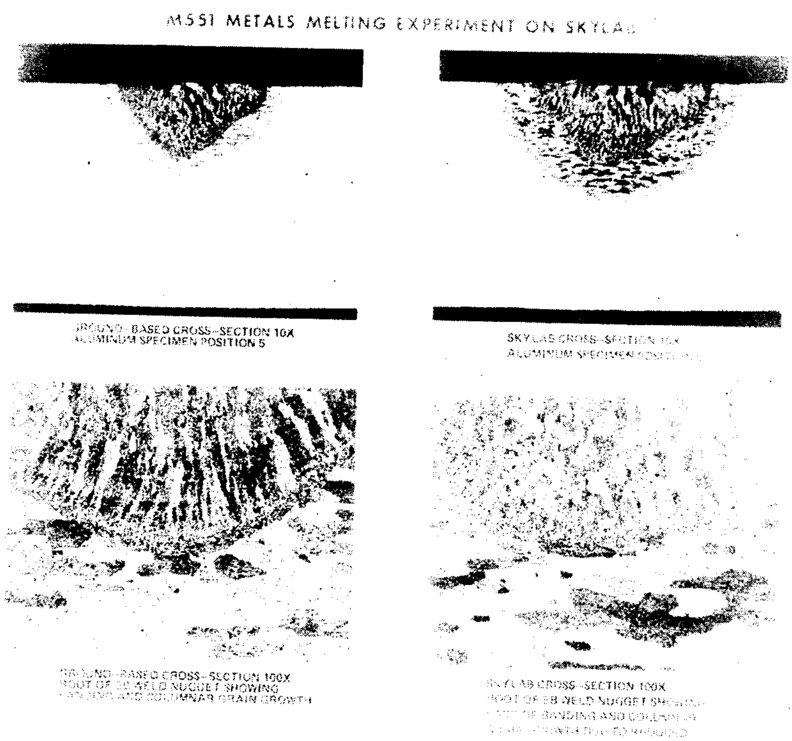


FIGURE 2 CROSS-SECTIONS THROUGH MELT GROOVE OF STAINLESS STEEL DISC

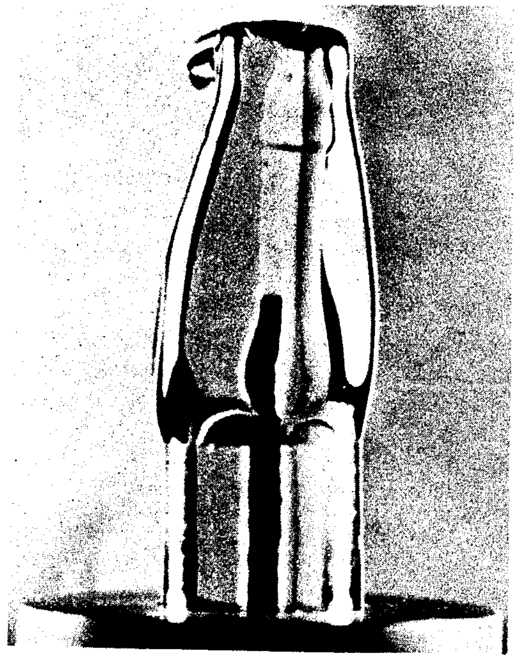
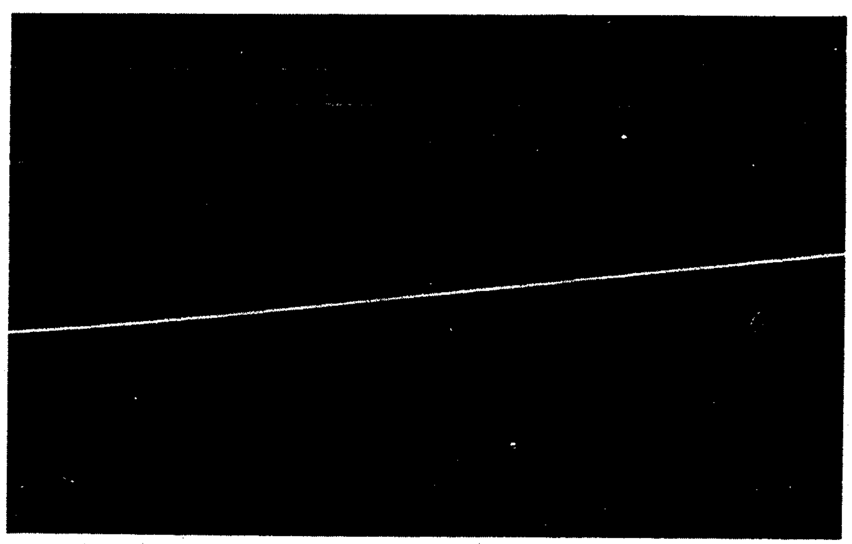


FIGURE 3 INDIUM-ANTIMONIDE CRYSTAL, RECRYSTALLIZED UNDER ZERO-GRAVITY

FIGURE 4 SPACE-GROWN (ZERO-GRAVITY) GERMANIUM-SELENIUM CRYSTALS

FIGURE 5 GERMANIUM-SELENIUM CRYSTALS, GROWN UNDER GROUND CONDITIONS



SEGMENT OF THE INITIAL REGROWTH INTERFACE OF TELLURIUM-DOPED InSb CRYSTAL. DOPANT INHOMOGENEITIES ARE SEEN IN THE EARTH-GROWN (UPPER) SECTION; NO DOPANT INHOMOGENEITIES ARE SEEN IN THE SPACE GROWN (LOWER) SECTION; 125X.

FIGURE 6 EARTH- AND SPACE-GROWN INDIUM-ANTIMONIDE CRYSTAL, DOPED WITH TELLURIUM

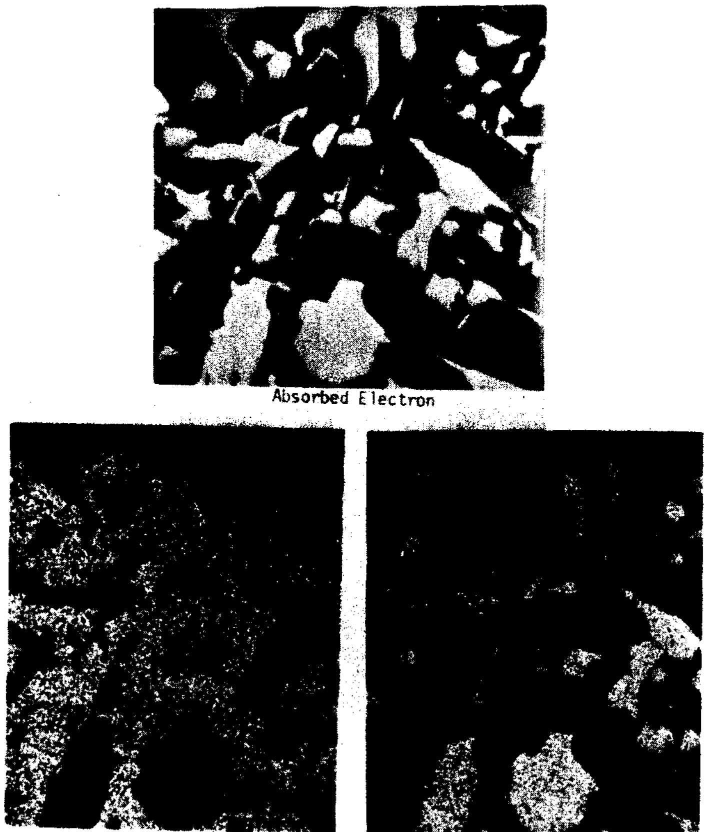


FIGURE 7 CROSS-SECTIONS THROUGH GOLD-GERMANIUM MIXTURE, MELTED AND SOLIDIFIED UNDER ZERO-GRAVITY

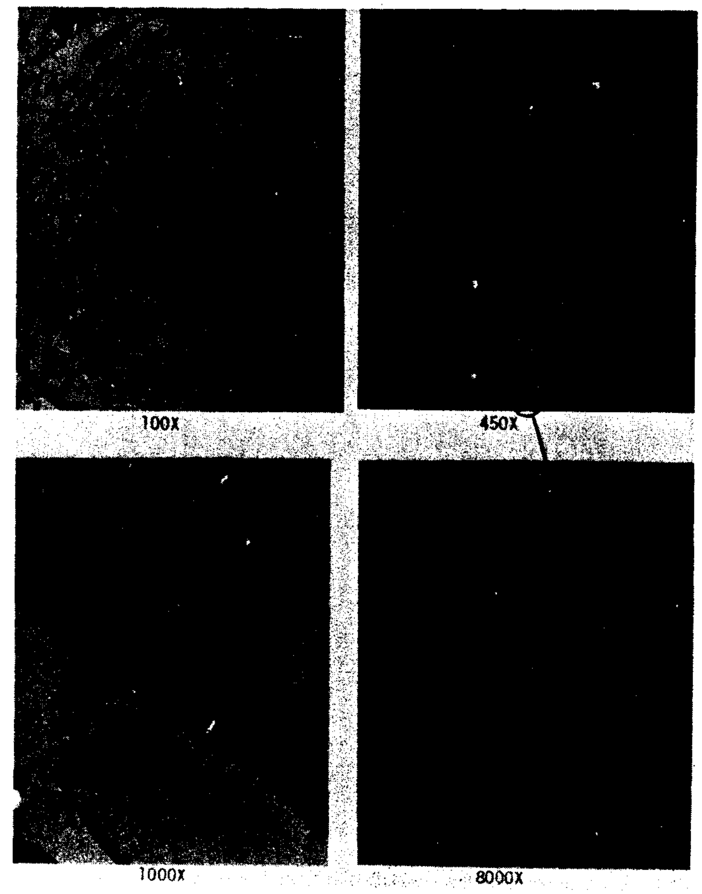


FIGURE 8 CROSS-SECTION THROUGH SPACE-PROCESSED GOLD-GERMANIUM MIXTURE, SHOWING NEW COMPOUND

	SKYLAB	APOLLO-SOYUZ	SPACELAB
METAL MELTING AND SOLIDIFICATION	X	X	X
METAL WELDING AND BRAZING	X		?
METAL MIXTURES, ALLOYS, COMPOUNDS	X	X	X
COMPOSITE MATERIALS	X	X	X
SEMICONDUCTORS (CRYSTALS)	X	X	X
SEMICONDUCTORS (DOPING)	X	X	X
SUPERCONDUCTORS	X		X
GLASSES			X
BIOMEDICAL SUBSTANCES		X	X

FIGURE 9 ZERO-GRAVITY EXPERIMENTS ON PAST AND FUTURE SPACECRAFT

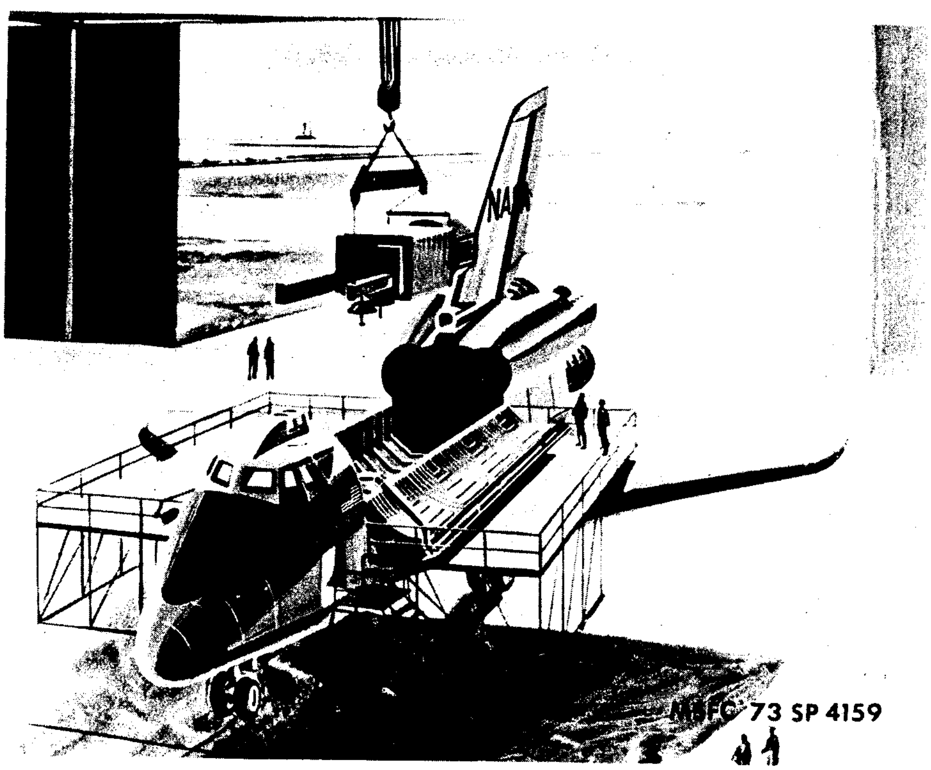


FIGURE 10 INSTALLING PAYLOAD IN SPACE SHUTTLE CARGO BAY

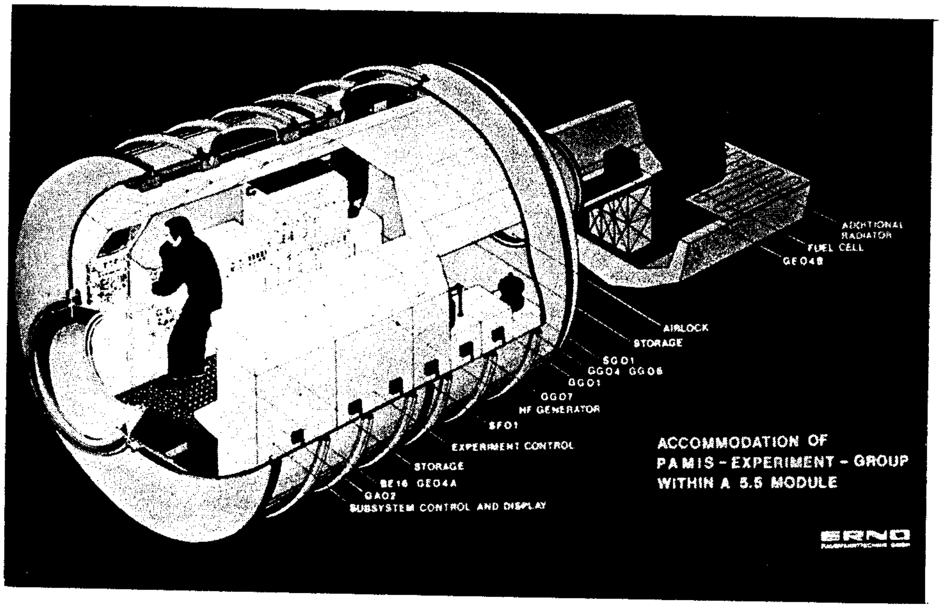


FIGURE 11 SPACELAB AND PALLET MODULES (ERNO CONCEPT)

TWO–WAY PAYLOAD FOR SHUTTLE (PRODUCTION FACILITY AND MATERIAL)	5 000	TO	9 000 KG
PRODUCTION QUANTITY PER FLIGHT	100	TO	2 000 KG
PRODUCTION QUANTITY PER YEAR			
WITH 1 FLIGHT PER MONTH	1 200	TO	2 400 KG
WITH 2 FLIGHTS PER WEEK	10 000	TO	200 000 KG

FIGURE 12 MATERIALS PROCESSING IN SPACE, PRODUCTION QUANTITIES OBTAINABLE ON SPACELAB